Buncher section

Introduction

Following the induction-linac rf bunching system a muon beam has been formed into a long bunch (full-width of 80m) with an average kinetic energy of 100 MeV and an rms energy width of ~6MeV. The transverse emittance of that beam is $\varepsilon_N \cong 0.01$ m-rad. With a continuous solenoidal focusing field of 1.25, this beam has an rms size of $\sigma_x \cong 7.3$cm.

This beam must be cooled and then accelerated into the muon storage ring, and affordable cooling and accelerator systems require (relatively) high frequencies, which implies relatively short bunches. The long bunches from the induction linac must be broken up into a string of shorter bunches matched to the cooling and accelerating rf.

Recent studies indicate that ~200 MHz rf cavities can provide adequate apertures for the large muon beams, and can be used for the cooling and initial acceleration sections of the neutrino source. Fermilab has experience and some equipment at 201.25 MHz rf, and that would be a possible specification for initial R&D and/or final development and construction. CERN has a supply of 350 MHz cavities which could be used for muon acceleration. If these cavities (or copies developed from them) are used, it is natural to choose a capture and cooling rf frequency that is a subharmonic (175MHz). In the present design studies 175 MHz and 200 MHz examples are used, and no substantial differences are obtained between them; final precise choices will depend on hardware availability.

The beam must also be matched in transverse phase space when transforming the beam from the decay and rf rotation section into the cooling section. The rf rotation section has a solenoidal focusing field of 1.25m, which means that the beam entering the buncher has $\beta^* \cong 1$m. The cooling system has a "FOFO" focusing structure which focuses the beam down to minima of β^* of 0.3m at the absorbers. In the present initial designs the cooling system begins with an absorber so the buncher must match the beam to a focusing waist with β^* of 0.3m at its exit.

Buncher options

Several scenarios for transforming the long-bunch beam from the induction linac into a string of short bunches have been proposed and these options have been described in ref. B-1. Three possible configurations have been discussed:

- A gradual bunching with 200 (or 175) MHz rf at fixed energy.
- An adiabatic match, starting with a lowered beam energy, and accelerating the beam to cooling energy.
- A short matching bunching rf, followed by a drift in which bunch length minimizes to match the cooling acceptance. This drift incorporates transverse matching.

The gradual bunching scenario leads to relatively large phase space dilution. At E=100 MeV (p_μ = 181 MeV/c), the energy spread is not well matched to the rf bucket size of 175 MHz rf, and a simple insertion of the beam into high-gradient rf would greatly dilute the phase space. A gradual increase of rf field as the bunch is transported along the linac can capture the bunch with smaller phase space dilution. However, an adiabatic capture at the scenario parameters would require a very long length; realistic lengths (<100m) give relatively large phase space dilution.

But if the beam energy is reduced, the parameters for adiabatic capture become more practical. As an example, we present a scenario with simulation results depicted in fig. 3. The central energy is reduced to 25 MeV, where the energy loss is assumed to occur through energy loss in a material. In the energy loss the energy spread increases to 4 MeV (in this example). The beam is then inserted into a bunching and accelerating linac, where the rf voltage is gradually increased from 1MV/m to 6MV/m while the synchronous phase increases from 90° to 72° over an 84m length. In the process 70% of the beam is captured in an accelerating bucket with the central beam energy increasing to 106 MeV while the energy spread increases to 12 MeV. The longitudinal emittance per bunch of the accelerated beam is 0.14 cm-GeV, compared to 0.20cm-GeV for the uncaptured initial beam. This indicates no phase space dilution in the adiabatic capture; the emittance decrease simply represents the uncaptured portion of the beam.

The initial beam energy, linac length, and rf increase program can be varied somewhat to obtain optimized matching in this capture and energy increase sequence, particularly if the initial and final beam parameters are somewhat different from our initial assumptions.

Rather than an adiabatic capture (with gradual increase of the bunching field) the bunching can be designed as a matched transport which takes the longitudinal phase space from the long bunch to a shorter bunch. Since the initial beam is quasi-continuous (that is, extends over many rf wavelengths), an rf system can only capture in matched format a portion of that beam. The optimization procedure is to obtain linear bunching over a maximal portion of the beam. In an initial example, we consider obtaining extended linear bunching by adding a second harmonic component (350 MHz) to a primary 175 MHz acceleration (sample parameters: 6MV/m at 175 MHz + (–1.5 MV/m) at 350 MHz for 3m). This provides linear bunching over a longer phase width than a single harmonic rf. The rf sytem is followed by a drift section (9m in this example), where the ramped beam converges toward a minimum bunch length which is longitudinally matched to the acceptance of a cooling channel.

The initial cooling channel would follow. This channel would have a mean energy loss with an accelerating and bunching rf; the stable phase of the accelerating rf is matched to the center of the bunch, with the mean cooling energy loss matched to the central acceleration ($dE/ds = eV' \cos \phi_s$). In an initial approximation the energy straggling through the cooling material is ignored, and we track the longitudinal capture motion through ~2 synchrotron periods (~60m).

Figure YY shows results of some simulations of this process. The initial beam approximates beam parameters at the end of the rf rotation: a long bunch with kinetic energy 100 MeV and rms energy spread of 6 MeV. The beam is bunched and matched into a 175 MHz cooling rf system with 12 MV/m of cooling rf and dE/ds = 6MV/m. In the simulation ~83% of the initial distribution is captured into a cooling bucket. The central ~70% of the initial beam is captured into the center of the cooling bucket with little phase space dilution, while the remainder of the captured beam appears as a filamented halo about the central core.

The beam nearly fills the cooling rf bucket and the beam is therefore vulnerable to losses due to energy straggling (rms energy width growth) in the cooling absorbers. An extended transverse cooling channel for this case would have a correspondingly greater need for some longitudinal cooling (or reduction of heating) than the previous smaller-dilution adiabatic capture case. However, both cases are vulnerable to the straggling effect, and more complete simulations of the cooling channel with straggling are needed to evaluate this effect, and determine what losses may occur and what improvements in the cooling scenario are needed.

Baseline Scenario

From the above options we have chosen a constant-energy matched bunching configuration as the baseline choice for the present design study. Parameters of the scenario are displayed in Table B2. It consists of a 4 m double-harmonic rf system (6MV/m at 175MHz + -1.5MV/m at 350 MHz),followed by a 7m drift with transverse matching magnets. This has been chosen because it is the simplest and shortest of the basic options and is expected to be easiest to implement within an initial design. It is also likely to be one of the less expensive options.

The initial 1-D simulations have been extended to 3-D simulations, using ICOOL and DPGeant, and the buncher parameterization has been modified to match the 3-D beam dynamics. For transverse matching from the 1.25-T transport of the capture section into the cooling section, a matching solenoid of 0.8 m length and 1.4 T peak field is added at the end of the bunching section. This is designed to match the beam to a waist at $\beta^* \cong 0.3$m.

Figure B-3 shows ICOOL simulation results for this case, showing the beam bunched to smaller bunch lengths and transverse beam sizes. There is little transverse emittance dilution in the process and only moderate longitudinal dilution.

This buncher configuration has been used in complete simulations of $\pi \rightarrow \mu$ capture, rf rotation and cooling, and the overall performance is in agreement with the section analyses.

Future Development efforts

We have presented an initial scenario for a buncher transforming the beam from the long bunch presented at the end of the rf rotation section to a string of bunches suitable for cooling by a high-frequency cooling system. This example has had only rudimentary initial optimization, and variations of it must be explored to obtain a best solution.

This initial design may also not be the optimal design concept and other options will be explored. A particularly attractive option is energy loss through absorbers to smaller beam energies (~25—50 MeV) followed by the adiabatic capture option. This enables an additional step of large emittance transverse cooling, and should have very little longitudinal emittance dilution, but may have more beam loss. This more complicated option will be developed and optimized in future studies for comparison with the present baseline.

References

1. David Neuffer, "RF Capture Variations for the Muon Storage Ring Neutrino Source”, MUCOOL-52 , July 1999.

Table B1- Beam Parameters before and after the Buncher section

Parameters are based upon a scenario starting with a single initial bunch of 3×10^{13} 16 GeV protons on target.

Beam Parameter	**Symbol**	**Before**	**After Buncher**
Number of muons	N_μ	6×10^{12}	4.5×10^{12}
μ mean momentum	p_μ	181 MeV/c	181 MeV/c
rms momentum spread	δp_μ	6	15 MeV/c
rms bunch length	σ_z	15m	20cm $\times$ 20bunches
rms transverse emittance	$\varepsilon_{\perp,N}$	0.01m-rad	0.01
rms beam size	σ_x	0.075m	0.042

Table B2 –Parameters of the Base Line Bunching section

RF SYSTEM

4m – double-harmonic rf system

6 MV/m 175MHz rf + -1.5 MV/m 350MHz rf

6m drift

Focusing system

1.25 T solenoid

last 0.8 meter has additional 1.4 T solenoid

match into cooling channel

Figure 3 Adiabatic capture at 175MHz – In this simulation the beam is decelerated to 25 MeV kinetic energy and from there the beam is adiabaticly captured by a gradually increasing rf voltage.

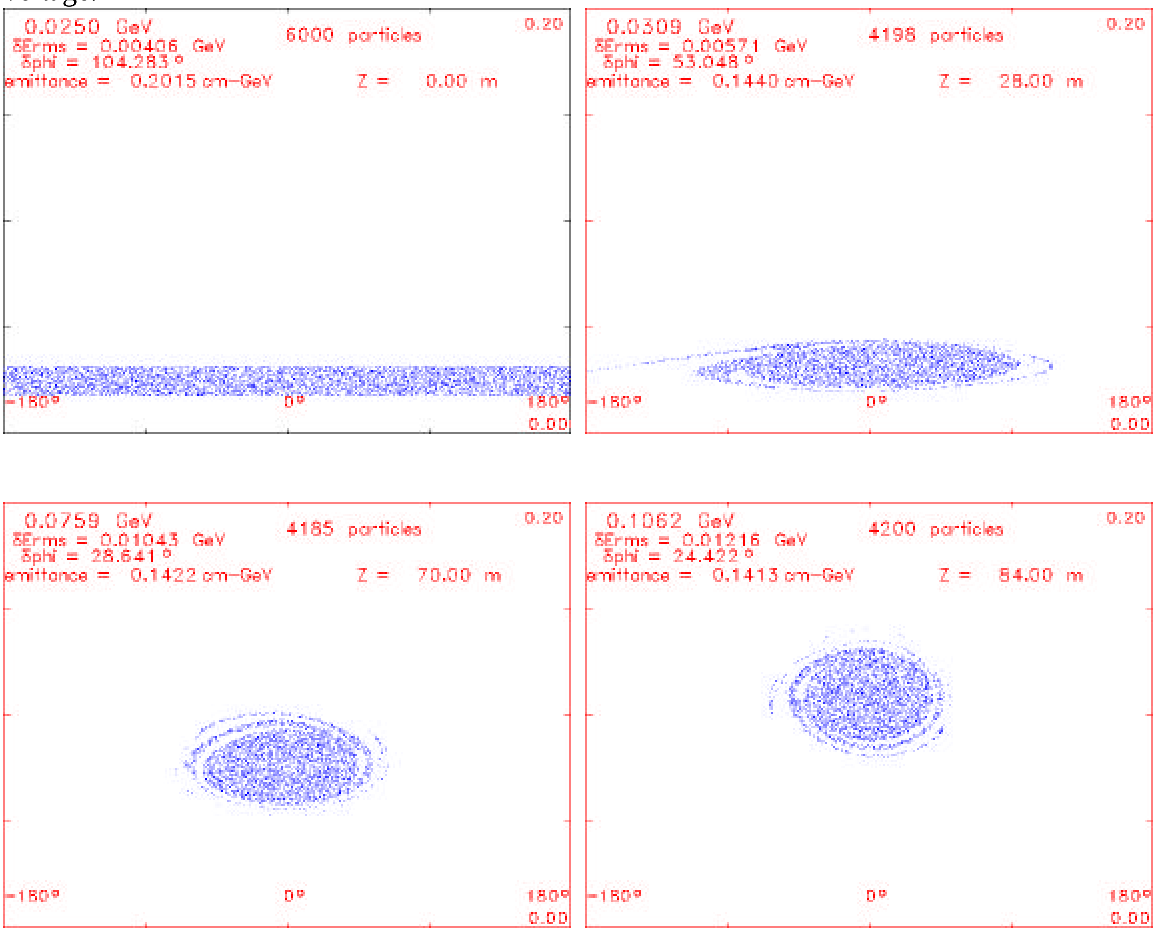


Figure 5 – matched capture with larger ΔE at the same parameters as fig. 4. Note that the initial beam is more closely matched to the cooling rf bucket size.

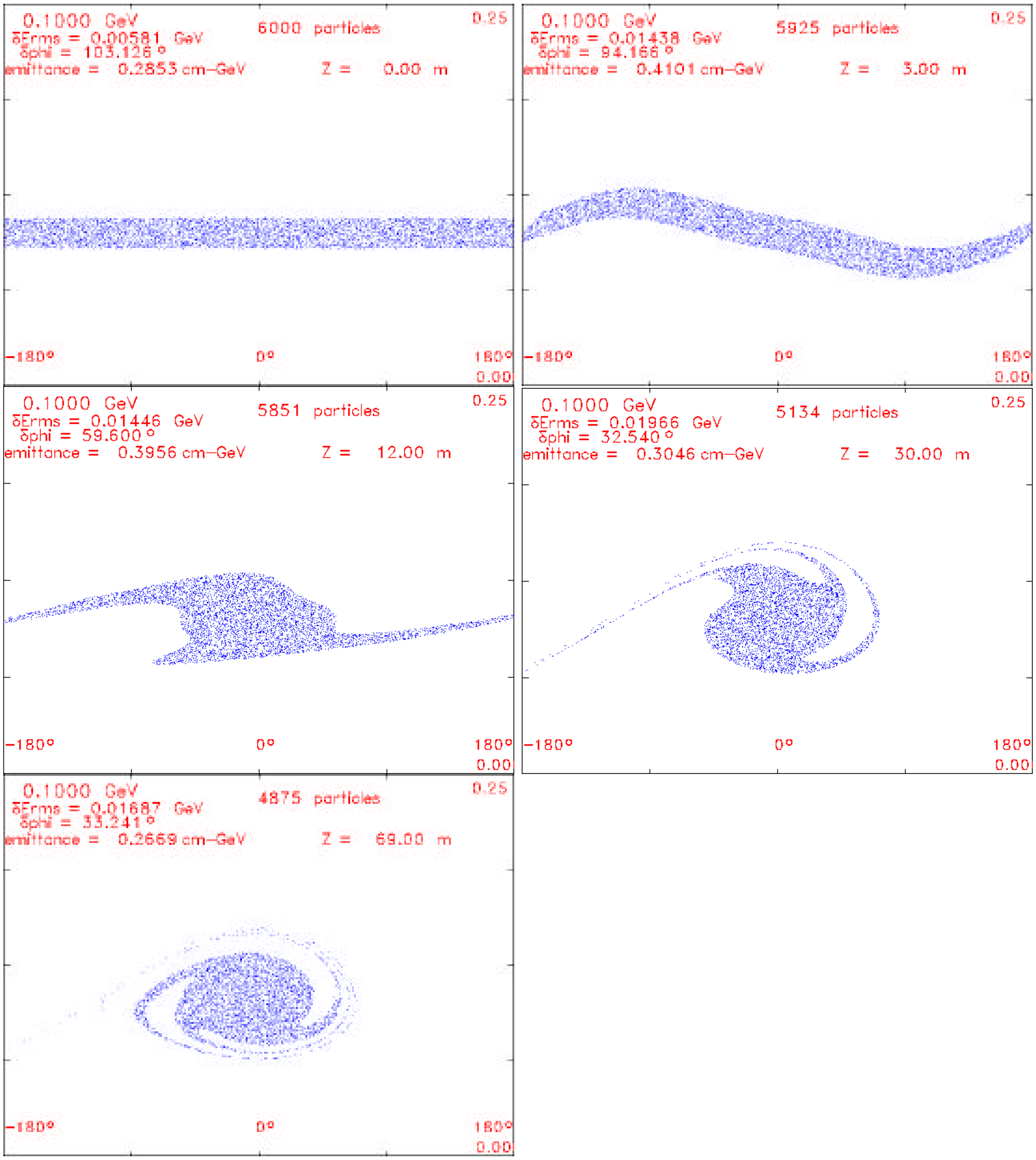
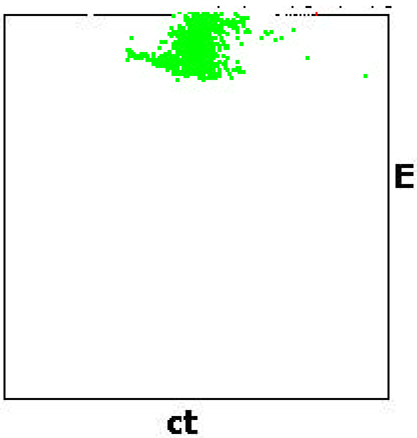
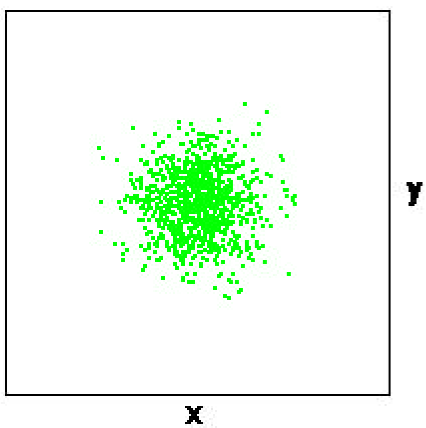


Figure : ICOOL simulation results for bunching into the cooling channel



Transverse match:



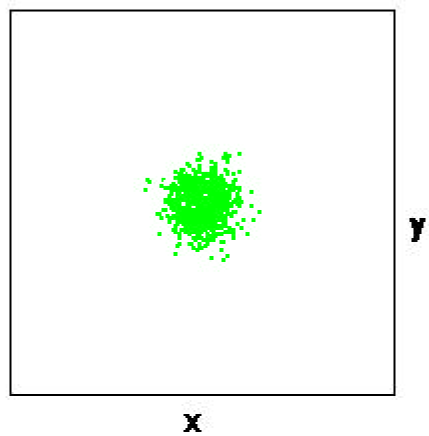


Figure XXX: Schematic Layout of Buncher section